

# Towards discrimination between galactic and intergalactic axion–photon mixing

Sergey Troitsky<sup>1,\*</sup>

<sup>1</sup>*Institute for Nuclear Research of the Russian Academy of Sciences,  
60th October Anniversary Prospect 7a, Moscow 117312, Russia*

There exists a growing evidence for the anomalous transparency of the Universe for energetic gamma rays. Popular explanations include conversion of photons into hypothetical axion-like particles (ALPs) and back in astrophysical magnetic fields. Two distinctive scenarios of this conversion have been put forward: either it happens in the (host galaxy of the) gamma-ray source and in the Milky Way, or the photon-ALP oscillations take place in the intergalactic magnetic fields all along the way between the source and the observer. Here we point out that, given recent astrophysical constraints on ALPs and on intergalactic magnetic fields, these two mechanisms imply very different ALP masses and couplings. Therefore, confirmation of the anomalies and identification of one of the scenarios would mean cornering of ALP parameters to a particular narrow region. We discuss approaches to distinguish between the two mechanisms and present some preliminary indications in favour of the galactic scenario.

PACS numbers: 14.80.Va, 95.85.Pw, 98.54.Cm

## I. INTRODUCTION

Since the early years of very-high-energy (VHE, above 100 GeV) gamma-ray astronomy, more and more distant sources have been discovered in this energy band, see e.g. Refs. [1–3]. This was surprising because gamma rays of these energies should interact with the background radiation to produce electron-positron pairs [4], the process which results in a strong suppression of the flux from distant sources. The apparent weakness of the suppression might be attributed either to overestimation of the amount of background radiation or to peculiar emission or absorption mechanisms at work in particular sources. However, recent studies indicate that these explanations are hardly relevant: modern models of extragalactic background light, e.g. Refs. [5, 6], used in the studies, already saturate lower bounds [7] from simple galaxy counts; while analyses of sets of distant sources [8–10] revealed unphysical redshift dependence in the required peculiar features of the emission spectra.

One of the most intriguing explanations of the ensemble of the data is that we might observe effects of a new hypothetical axion-like particle (ALP) (see Ref. [11] for a review). Depending on parameters of the ALP and on values of the intergalactic magnetic field (IGMF), two scenarios may work. Photon-ALP oscillations in IGMF may effectively increase the photon mean free path [12–14]. Alternatively, if IGMF is weak, photons may efficiently convert to ALPs in the source [15] or in its neighbourhood, cluster or filament [16], with reconversion back to photons in, or close to, the Milky Way. The main purpose of this study is to emphasise differences between the

two scenarios and to demonstrate that, given recent astrophysical constraints, they correspond to distinguishable ALP parameters. The key new ingredients contributing here are the reanalysis of the supernova (SN) 1987A data [17] and new upper limits on intergalactic magnetic fields [18]. We also present some evidence in favour of the galactic scenario and discuss future observations which may help to discriminate between the two options (see also Refs. [19, 20]).

The rest of the paper is organized as follows. In Sec. II, we briefly review the evidence for the anomalous transparency of the Universe for gamma rays. In Sec. III, we describe two scenarios of the ALP-photon mixing which may explain the observed evidence. Then, we compare required ALP parameters, calculated by means of detailed analyzes elsewhere, with recent astrophysical bounds and present argumentation for the main point of the paper. In Sec. IV, we consider ways to distinguish the two scenarios and present some evidence in favour of one of them. Future prospects to test the ALP explanation of the anomalous transparency of the Universe for gamma rays and to single out one of the scenarios, thus constraining the ALP parameters, are discussed in Sec. V.

## II. EVIDENCE FOR ANOMALOUS TRANSPARENCY

The modern evidence for the anomalous transparency of the Universe for energetic gamma rays is based on studies of ensembles of distant VHE sources. The observed spectra of these sources have been corrected for the pair-production effects (“deabsorbed”) within the most conservative, i.e. lowest-absorption, models, to obtain intrinsic spectra emitted at the sources. These in-

---

\* st@ms2.inr.ac.ru

trinsic spectra exhibit unphysical redshift dependence which is readily interpreted as an overestimation of the absorption even in the minimal models.

Upward breaks, or unusual spectral hardenings, have been found in *deabsorbed* spectra of many individual sources (see e.g. Ref. [2]). Statistically significant hardening never presents in observed spectra which, contrary, often exhibit mild softening at high energies. In 2012, Horns and Meyer analysed [8] a sample of 7 blazars observed at optical depths  $\tau > 2$  with respect to the pair production. The blazars were observed by imaging atmospheric Cerenkov telescopes (IACTs) and have redshifts  $z \lesssim 0.536$ . They found an evidence that positions of the upward breaks in deabsorbed spectra of blazars change with redshift in such a way that they always occur at the energy where the absorption becomes important. This was surprising because astrophysical properties of blazars in the sample were very similar for close and distant sources. The probability that this effect is a chance fluctuation, estimated in Ref. [8] by a statistical procedure based on the Kolmogorov-Smirnov test, corresponds to that of a  $4.2\sigma$  fluctuation in a Gaussian distribution.

Rubtsov and Troitsky [9] considered in 2014 a sample of 20 blazars observed at optical depths  $\tau > 1$ . IACT results have been supplemented with the FERMI-LAT data, which allowed to extend the redshift range up to  $z \approx 2.156$ . Assuming the breaks in deabsorbed spectra at energies for which  $\tau = 1$ , we found that the strength of the break, that is the difference between the power-law spectral indices below and above the break point, is a function of the redshift and does not depend on the physical properties of a blazar. The statistical significance of this unphysical dependence, indicating overestimation of the absorption and therefore an anomaly, has been calculated in Ref. [9] by means of the usual  $\chi^2$  analysis and corresponds to a  $12.4\sigma$  fluctuation of a Gaussian.

In 2015, Galanti et al. [10] considered a sample of 39 blazars ( $z \lesssim 0.536$ ) detected in VHE gamma rays, independently of the opacities tested. They described deabsorbed spectra as power-law functions and did not fit the spectral breaks. The power-law spectral index was found to be redshift-dependent, which is not expected in any astrophysical model and again indicates the anomaly. This result confirms the observation of Ref. [9] though the intrinsic scatter of spectral indices and the limited redshift range make the result less pronounced than in the break study.

The significance estimates quoted above are based on statistical analyses only and are subject to systematic uncertainties, which are discussed in Refs. [8, 9]. In particular, Ref. [8] shows that under the worst assumptions about systematic errors, the significance of the effect is reduced by  $\sim 1.6\sigma$ . Ref. [9] presents several tests of the robustness of the result; however, a detailed quantitative study of systematic uncertainties is hardly possible without a complete sample of sources (tests of the Malmquist bias have been presented in Ref. [9] for the part of the sample taken from the FERMI-LAT catalog).

Recently, Biteau and Williams [21] criticised the results of Horns and Meyer [8] and claimed they do not see any anomaly in the ensemble of deabsorbed spectra of 38 blazars observed by IACTs. Since they did not select the blazars by the energies at which the data are available, their sample is dominated by the sources for which the absorption is, and should be, low or negligible (as we know from Ref. [9], only 15 blazars were firmly observed by IACTs at  $\tau > 1$ , and [8] only 7 at  $\tau > 2$ ). In addition, they used multiple spectra for a given blazar in their work; this introduces additional statistical weight to better-studied nearby, and therefore unabsorbed, sources. Even for heavily absorbed sources, they apply a different method to derive their own model of background radiation and the intrinsic spectrum. All these points might explain the discrepancy between Refs. [21] and [8] which Biteau and Williams attribute to the use of the Kolmogorov-Smirnov test by Horns and Meyer. In any case, this critique is irrelevant to our work [9] in which we made use of the usual  $\chi^2$  test to determine the significance of the anomalous transparency in a clean sample.

The only astrophysical explanation of these anomalies [22] requires some non-conventional assumptions. It assumes that a sufficient number of ultra-high-energy cosmic protons are accelerated in precisely the same gamma-ray blazars. Unless extragalactic magnetic fields are as low as  $\lesssim 10^{-17}$  G everywhere along the line of sight, this scenario may have tensions with the observation of fast variability of 4C+21.35 at very high energies [23]. In what follows, we assume the anomalies are real and concentrate on a different kind of their explanations.

### III. EXPLANATIONS

The problem of unphysical spectral breaks may be alleviated if the gamma-ray attenuation is reduced by means of some mechanism. Indeed, the breaks are seen precisely at the energies where the correction for attenuation becomes important (lower energies for larger distances); reduction of the attenuation diminished the correction and removes the breaks [9]: given observed softening of high-energy spectra, one may even obtain expected power-law shapes if the absorption is present but reduced. However, the usual deabsorption procedure is based on firm standard physics and very conservative assumptions about the photon background, so only new-physics effects might help. Besides the possibility of the Lorentz-invariance violation, the only known explanation involves ALPs.

An ALP mixes with photons in external magnetic field [24], which may allow to suppress the attenuation due to pair production: gamma-ray photons convert to ALPs, then travel unattenuated and eventually convert back to photons. The photon beam is still attenuated, but the flux suppression becomes less severe. A useful collection of formulae describing the mixing for astrophysical environments, as well as a quantitative discus-

sion of various scenarios, may be found in Ref. [16]. To reduce the opacity of the Universe for TeV gamma rays from blazars, two particular scenarios involving ALPs are important. The purpose of the present study is to emphasise and to explore the difference between the two approaches.

The first scenario implies that the intergalactic magnetic field is strong enough to provide for ALP/photon conversion all along the path between the source and the observer. Originally suggested in Ref. [12] in a different context, this mechanism, known also as the DARMA scenario, was invoked for the TeV blazar spectra in Ref. [13]. If it is at work, then the photon/ALP mixed beam propagates through the Universe and, since the photons are attenuated while ALPs are not, the effective suppression of the flux is smaller compared to the pure-photon case. It is easy to demonstrate that, for a sufficiently long propagation through domains of randomly oriented magnetic fields, the optical depth is effectively reduced by 2/3 in this scenario. A more detailed study is given, for instance, in Ref [10], from where the most recent constraints on the relevant ALP parameters are obtained: the ALP mass  $m \lesssim 10^{-9}$  eV and the ALP-photon coupling  $g_{a\gamma\gamma}$  determined from  $\xi \equiv (B/\text{nG})(g_{a\gamma\gamma} \times 10^{11} \text{ GeV}) \gtrsim 0.3$ , that is  $g_{a\gamma\gamma} \gtrsim 3 \times 10^{-12} \text{ GeV}^{-1}$ . In what follows, we will refer to this mechanism as the “intergalactic conversion” and use the parameter constraints [10] for this scenario.

The second approach assumes that there are quite strong magnetic fields inside or around the source, as well as around the observer, while for the most part of the distance the beam travels in weak magnetic fields, insufficient for ALP/photon mixing. The conversion may happen either in the blazar itself and in the Milky Way [15] or in the galaxy cluster or filament [16] (see also a more detailed subsequent study in Ref. [25]) containing the source and the observer, in various combinations. To get a qualitative idea of the effect of this mechanism on the gamma-ray attenuation, one might consider the case of maximal mixing, which is certainly an unrealistic oversimplification for many particular sources. Then 1/3 of the original photon flux is converted into ALPs close to the source while the remaining 2/3 attenuate in a usual way. Close to the observer, 2/3 of the ALPs convert back to gamma rays and may be detected. A more detailed recent study of this mechanism is presented in Ref. [19], where it is called “the general-source” scenario. Notably, this scenario requires  $g_{a\gamma\gamma} \gtrsim 2 \times 10^{-11} \text{ GeV}^{-1}$  because for lower values of the coupling, the path of the ALP-photon beam would be too short for efficient conversion even for maximal mixing (the Hillas-like argument). In the rest of the paper, we refer to this mechanism as the “galactic conversion” and use parameter constraints derived in Ref. [19] for this case<sup>1</sup>.

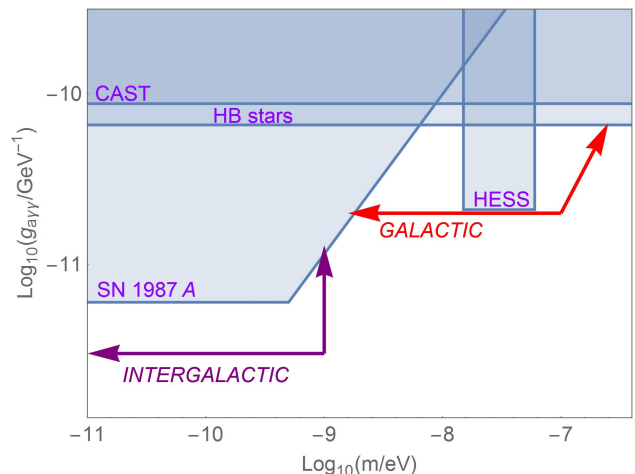


FIG. 1. The ALP parameter space (ALP-photon coupling  $g_{a\gamma\gamma}$  versus ALP mass  $m$ ) with current constraints (see text). Regions corresponding to the Galactic [10] and intergalactic [19] ALP/photon conversion explanations of the gamma-ray anomalies are indicated; they extend to the excluded regions as shown by arrows. Given all constraints, the two regions are well separated.

Clearly, if we knew the values of IGMF, it would be quite easy to choose between the two scenarios. Unfortunately, the values are a subject of strong debates, and we have to seek other ways to disentangle the two options.

Parameters of the ALP, that is  $m$  and  $g_{a\gamma\gamma}$ , required for efficient operation of one or another mechanism, have been discussed in Refs. [10, 16, 19]; we refer the reader to these works for details of the derivation. Theoretically, they overlap in a large range of allowed parameters. However, when the most recent experimental and astrophysical constraints are taken into account, the parameter regions allowed for the two scenarios become disconnected; this means that if we determine that one or another scenario works in Nature, we strongly constrain the ALP mass and coupling! We illustrate this fact in Fig. 1, where shaded blue areas, excluded by constraints from the CERN axion solar telescope (CAST, Ref. [26]), evolution of the horizontal-branch (HB) stars [27], re-analysis of the SN 1987A data [17] and HESS constraints from the absence of irregularities in a blazar spectrum [20], indicate the most restrictive relevant limits.

One may see that the key constraint contributing to the separation of the two regions is that of Ref. [17]. It was obtained from non-observation of the gamma-ray flare corresponding to the SN 1987A explosion by the Gamma-Ray Spectrometer of the Solar Maximum Mission. The fluence limits used for the constraint are 99% CL; however, the response of the instrument to photons at large angles to viewing directions, relevant for

<sup>1</sup> In Fig. 1 below, the corresponding line was smoothed with re-

spect to that of Fig. 4 of Ref. [19] since we believe the features presented there are overprecise, given observational uncertainty in GMF.

SN 1987A, is quite uncertain. The authors of Ref. [17] use results of the previously published Monte-Carlo simulations. One may ask then, maybe the limit of Ref. [17] is wrong and the point of the present paper is destroyed? The answer is no. Indeed, for  $m \lesssim 10^{-9}$  eV, where the intergalactic scenario may work with  $B$  satisfying the observational limits, the constraint [17] reads as  $g_{a\gamma\gamma} \lesssim 5 \times 10^{-12} \text{ GeV}^{-1}$ , while the galactic scenario requires  $g_{a\gamma\gamma} \gtrsim 2 \times 10^{-11} \text{ GeV}^{-1}$ , that is four times higher. Since the  $g_{a\gamma\gamma}$  limit changes as the fourth root of the fluence, the two inequalities for  $g_{a\gamma\gamma}$  might be brought into agreement by a  $\sim 4^4 = 256$  times error in the effective area. Clearly, even a rough estimate of the effective area of a satellite experiment can hardly be a factor of 256 wrong.

The separation of the two regions, which are often unified in a single large band referred to as the “transparency hint” in relevant plots, is remarkable. It is instructive to compare this result with those of Ref. [19] which, if considered superficially, suggest that the two mechanisms may work at the same time. However (see Fig. 4 of Ref. [19]), this might happen only in the “optimistic” scenario with the IGMF strength of 5 nG, now excluded by the study of Faraday rotations of distant sources [18]. We use parameters from the most recent study of the intergalactic scenario [10] which, though published before Ref. [18], does not assume IGMF in excess of the new limit, 1.2 nG. Hence, the probability of conversion in IGMF is lower and the parameter region is shrunk, compared to Ref. [19].

There exist some concerns about the possibility of efficient axion-photon conversion in blazars, see Ref. [28]. The key ingredient in this reasoning is the Quantum Electrodynamics (QED) strong-field term which becomes important at

$$\left(\frac{B}{\text{G}}\right) \left(\frac{E}{100 \text{ GeV}}\right) \sim 0.75, \quad (1)$$

see e.g. Ref. [16] (the ALP-photon mixing in this regime may also be affected by photon-photon dispersion, see Ref. [29]). The concerns are however not critical for the galactic conversion scenario for the following reasons. Ref. [28] considers separately BL Lac type objects (BLLs) and flat-spectrum radio quasars (FSRQs). For BLLs, assuming magnetic fields  $B \sim (0.1 - 1)$  G at the site where gamma rays are produced, the condition (1) is approached at the energies of interest, so the photon-ALP conversion probability may depend strongly on unknown details of the environment and becomes hardly predictable. However, if ALP parameters allow for the conversion in the Milky Way, one expects that the conversion in a BLL host galaxy or cluster is also allowed<sup>2</sup>, and the galactic scenario may work. The situation is more

contrived for FSRQs, for which, in Ref. [28], magnetic field values  $B \sim (1 - 10)$  G are assumed (for the gamma-ray emitting region). The QED term starts to suppress the photon/ALP conversion at energies  $E \gtrsim 10$  GeV in this region, but efficient conversion is possible in outer parts of the galaxy and the cluster. It may be tricky for gamma rays above  $E \sim 20$  GeV to get there because of intense pair production in the broad-line region, presumably located between the gamma-ray emitting site and the lobe. However, one may point out that gamma rays up to several hundred GeV have been observed from FSRQs [1, 23] (see Ref. [32] for a discussion of ALP explanation of the observation [23]), which means they escape the broad-line region somehow. Once escaped, they may equally well convert to ALPs outside.

#### IV. DISCRIMINATION BETWEEN GALACTIC AND INTERGALACTIC SCENARIOS

**Anisotropy.** The magnetic field of the Milky Way galaxy has a complicated structure, and the probability of the ALP/photon conversion there, which is required in the galactic scenario, depends strongly on the direction. Evidence for direction dependence in the anomalous transparency of the Universe may therefore be a strong argument in favour of the galactic scenario [15, 16, 33].

In Ref. [15], it was pointed out that the positions of a few TeV blazars with redshifts  $z > 0.1$  known by that time fit surprisingly well the regions in the sky where the conversion probability, calculated within the model of the Galactic magnetic field (GMF) of Ref. [34], are high. Here, we assume this as a hypothesis and attempt to test it with new observational data. Clearly, more elaborated approaches should be used in further studies (see Ref. [33] for an attempt on which we comment below and Ref. [35] for a different approach). We consider a sample of blazars with firm detection beyond  $\tau = 1$  which consists of 15 objects observed by IACTs and 5 objects observed by FERMI LAT (the sample of Ref. [9]), supplemented by additional 6 blazars rejected in Ref. [9] because of the insufficient number (4 with 5 required) of data points for fitting spectra with breaks. We drop 4 nearby objects with  $z < 0.1$  from the sample, like it was done in Ref. [15].

Figure 2 represents the distribution of these objects in the sky together with the conversion probability for the same magnetic-field model [34]. Though there exist more elaborated modern GMF models [36, 37], the test of the original claim should be performed with the same

<sup>2</sup> One should note, however, that the host galaxies of blazars are elliptical while the Milky Way is spiral. While the strength of

the magnetic field in the Milky Way is assumed to be typical, elliptical galaxies contain fewer cosmic-ray electrons, and hence less synchrotron emission, making detection of the galaxy-scale magnetic fields tricky and, for today, uncertain [30]. Qualitative theoretical arguments suggest [31] small correlation length for the turbulent field. In any case, giant elliptical galaxies often reside in groups or clusters whose magnetic field also allows for the photon-ALP conversion.

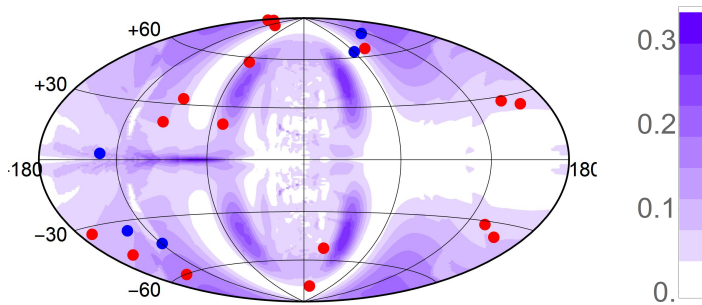


FIG. 2. The skymap (Galactic coordinates, Hammer projection) with positions of blazars with detected gamma-ray flux at energies for which  $\tau > 1$  (red,  $0.1 < z < 1$ ; blue,  $z > 1$ ), see text. Deeper shading corresponds to higher ALP-photon conversion probability in the Milky Way (the Galactic magnetic field model of Ref. [34]).

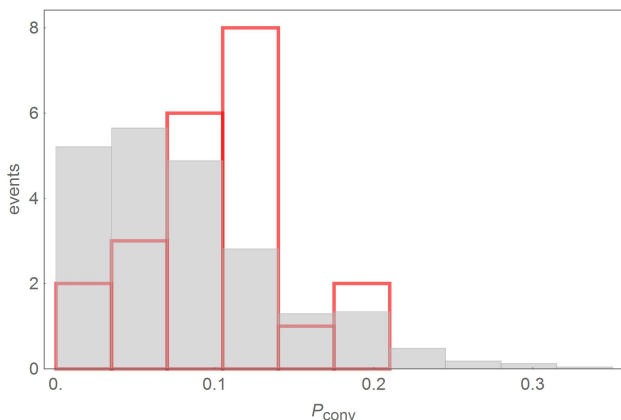


FIG. 3. The distribution of the values of the ALP-photon conversion probability in the Milky Way calculated for directions to blazars with detected gamma-ray flux at energies for which  $\tau > 1$  (red line) and for random isotropic directions (gray shading).

one. The objects indeed follow the regions of high conversion probability, qualitatively confirming the trend seen in Ref. [15]. Two of 22 objects are seen in the regions of low conversion probability; this may be well understood given uncertainties in the GMF models.

It is not possible, however, to rigorously test the hypothesis quantitatively, because the blazars we discuss do not form a complete isotropic sample. While 5 FERMI-LAT sources were selected from a more or less uniform full-sky data, the remaining 17 objects were arbitrarily chosen for observations with pointed runs of small-field-of-view IACTs. Nevertheless, for illustration, we present here the results of a simple statistical test of the hypothesis, keeping in mind its qualitative level. For each of the 22 sources in the sample, we calculate the ALP/photon conversion probability in the GMF of Ref. [34]. The same distributions were calculated and averaged for 100 sets of 22 objects distributed isotropically in the sky. Figure 3 compares the distributions. The Kolmogorov-Smirnov

probability that the distribution seen for the real data is a fluctuation of that for simulated directions is 0.02. We do not assign any statistical significance to this result for the reasons mentioned above (incomplete sample), though the entire picture does not contradict the galactic conversion scenario.

Another approach to test the anisotropy effect was suggested by Wouters and Brun [33]. They proposed to study autocorrelation patterns in the directional distribution of differences between FERMI-LAT and TeV spectral indices of blazars. We note that these differences are not equal to the spectral breaks discussed in Sec. II since the breaks happen at distance-dependent energies, not always between the bands considered in Ref. [33]. The procedure is motivated by the fact that, due to our limited knowledge of the GMF, actual conversion probabilities vary strongly from one GMF model to another, while all models predict patchy large-scale anisotropy in the distribution of these probabilities. However, as they show themselves [33], the patterns in the autocorrelation function also vary strongly from model to model. Clearly, quantitative estimates of statistical significance would require a complete sample of sources in this approach, similarly to a more direct approach [15] we discuss here.

**Distant objects.** In the ideal case and in the long-distance limit, the effective optical depth  $\tau_{\text{ALP}}$  behaves differently in the two scenarios: for intergalactic conversion,  $\tau_{\text{ALP}} \sim (2/3)\tau$  (and therefore grows approximately linearly with distance, like the standard optical depth  $\tau$ ), while for the galactic scenario, assuming maximal mixing, it reaches a constant, distance-independent value corresponding to the flux suppression by a factor of  $\sim 2/9$ , that is  $\tau_{\text{ALP}} \sim 1.5$ . At a certain redshift  $z_{\text{crit}}$ , which value depends on the details of the absorption model and of magnetic fields assumed, the two suppression factors are equal, while beyond  $z_{\text{crit}}$ , the effective absorption becomes stronger and stronger in the intergalactic scenario, remaining essentially constant in the galactic one. This means that for very high redshifts, the anomalous transparency effect would hardly be seen in observations for the intergalactic scenario, therefore any evidence for the effect for very distant sources speaks in favour of the galactic conversion. The blazars observed by IACTs have measured spectroscopic redshifts up to  $z = 0.536$  (3C 279; a lower limit of  $z > 0.6$  exists for PKS 1424+240), and all anomalous-transparency effects derived from them are equally well described by both mechanisms. However, inclusion of much more distant blazars, for which the absorption becomes significant at energies in the FERMI-LAT band, changes the picture: the 12-sigma anomaly reduces to  $\sim 5\sigma$  (and therefore remains present) when intergalactic conversion is assumed, in addition to the usual absorption, but diminishes to  $\sim 2\sigma$  (and therefore disappears) for the assumption of the galactic scenario [9]. While these results have been obtained in a simplified approach, the difference between scenarios is so pronounced that it could hardly be removed by any detailisation of the analysis. Prospects for

observations of distant gamma-ray sources are discussed, in the ALP context, in Ref. [38].

**Intergalactic magnetic fields.** The intergalactic scenario requires rather high IGMF,  $B \sim (10^{-10} - 10^{-9})$  G, otherwise the conversion probability would be too low. The value of IGMF is irrelevant for the galactic scenario provided the SN 1987A constraints on ALP parameters are satisfied. Present-day knowledge does not allow for a firm conclusion about the real values of  $B$ . A number of constraints are summarized in the review [39]. The most stringent observational limit, based on the redshift independence of the Faraday rotation from distant sources, is  $B \leq 1.2 \times 10^{-9}$  G [18]. Constrained simulations of IGMF [40] favour the values of  $B \sim (10^{-12} - 10^{-11})$  G in voids (see however Refs. [41–43], advocating somewhat larger values from unconstrained simulations and semi-analytical models). The angular correlation function of FERMI-LAT photons points to  $B \sim 5 \times 10^{-14}$  G [44]. There exist several claims of observations of the pair halo around gamma-ray sources which suggest IGMF values in the range of  $B \sim 10^{-14}$  G, see e.g. Ref. [45] for a recent one, but these analyses are technically involved and require further confirmation.

## V. FUTURE TESTS

While all three methods to distinguish between the two scenarios, discussed in Sec. IV, favour weakly the galactic conversion mechanism, it is clear that more tests are required both to confirm the anomalous transparency of the Universe and to single out its explanation. To approach the tests on more solid grounds, future observations are necessary. Of particular importance are spectral and anisotropy studies, for which the following directions are especially important:

- to enlarge the overall statistics of TeV blazars, which is best achieved with the coming Cerenkov Telescope Array (CTA) [46];
- to study absorption effects in the spectra of the most distant blazars, for which one needs high-sensitivity observations at energies  $\sim (10 - 100)$  GeV. The sensitivities of both FERMI LAT and CTA are insufficient in this energy range; the

solution may be provided by high-altitude low-threshold Cerenkov detectors [47]. Presently, two projects of this kind are under consideration, the Atmospheric Low Energy Gamma-Ray Observatory (ALEGRO) in Atacama, Chile, and the Elbrus Gamma-Ray Observatory (EGO) at the Mount Elbrus, Russia;

- to move into the strong-absorption energy range for bright nearby blazars, which would require observations at  $\sim 100$  TeV. The proper instruments for that would be extensive-air-shower detectors, in particular, the Tunka Advanced Instrument for cosmic-ray physics and Gamma-ray Astronomy (TAIGA) [48] and the upgraded Carpet array at the Baksan Neutrino Observatory [49] in the nearest future. Several years later, the Large High Altitude Air Shower Observatory (LHAASO) will provide the best sensitivity [50]. Another relevant future project is HiSCORE [51].

Additional important contributions to the discussion are expected from observational constraints on the IGMF values. Note that the improvement in the limits on  $B$  by a factor of two would be sufficient to independently exclude the intergalactic scenario. Such an improvement may be achieved after the data of the planned all-sky rotation-measure grid [52, 53], planned for the Square Kilometer Array (SKA), will become available. Of course, constraints on  $g_{a\gamma\gamma}$  from laboratory searches for the responsible ALP would be crucial, with the most sensitive planned instrument being the International Axion Observatory (IAXO) [54], for which the entire range of photon-ALP couplings suggested in both scenarios we discussed is within the discovery range. The upgraded Any Light Particle Search (ALPS-II) [55] experiment will approach the interesting range of couplings and probe a part of the parameter space for the galactic scenario.

## ACKNOWLEDGMENTS

The author is indebted to G. Galanti, M. Meyer, M. Pshirkov, M. Roncadelli and G. Rubtsov for interesting discussions. This work was supported in part by the RFBR grant 13-02-01293.

- 
- [1] E. Aliu *et al.* [MAGIC Collaboration], “Very-High-Energy Gamma Rays from a Distant Quasar: How Transparent Is the Universe?,” *Science* **320** (2008) 1752 [arXiv:0807.2822 [astro-ph]].
  - [2] S. Archambault *et al.* [VERITAS and Fermi-LAT Collaborations], “Deep Broadband Observations of the Distant Gamma-ray Blazar PKS 1424+240,” *Astrophys. J.* **785** (2014) L16 [arXiv:1403.4308 [astro-ph.HE]].
  - [3] Y. T. Tanaka *et al.*, “Fermi Large Area Telescope Detection of Two Very-high-energy ( $E > 100$  GeV) Gamma-Ray Photons from the  $z = 1.1$  Blazar PKS 0426–380,” *Astrophys. J.* **777** (2013) L18 [arXiv:1308.0595].
  - [4] A.I. Nikishov, “Absorption of high-energy photons in the Universe,” *Sov. Phys. JETP* **14** (1962) 393 [ZhETF **41** (1962) 549].
  - [5] A. Franceschini, G. Rodighiero and M. Vaccari, “The extragalactic optical-infrared background radiations, their

- time evolution and the cosmic photon-photon opacity,” *Astron. Astrophys.* **487** (2008) 837 [arXiv:0805.1841].
- [6] G.R. Gilmore, R.S. Somerville, J.R. Primack and A. Dominguez, “Semi-analytic modeling of the EBL and consequences for extragalactic gamma-ray spectra,” *Mon. Not. Roy. Astron. Soc.* **422** (2012) 3189 [arXiv:1104.0671].
- [7] R.C. Keenan, A.J. Barger, L.L. Cowie and W.-H. Wang, “The Resolved Near-infrared Extragalactic Background,” *Astrophys. J.* **723** (2010) 40 [arXiv:1102.2428].
- [8] D. Horns and M. Meyer, “Indications for a pair-production anomaly from the propagation of VHE gamma-rays,” *JCAP* **1202** (2012) 033 [arXiv:1201.4711 [astro-ph.CO]].
- [9] G. I. Rubtsov and S. V. Troitsky, “Breaks in gamma-ray spectra of distant blazars and transparency of the Universe,” *JETP Lett.* **100** (2014) 355 [Pis'ma ZhETF **100** (2014) 397] [arXiv:1406.0239 [astro-ph.HE]].
- [10] G. Galanti et al., “Axion-like particles explain the unphysical redshift-dependence of AGN gamma-ray spectra,” arXiv:1503.04436 [astro-ph.HE].
- [11] J. Jaeckel and A. Ringwald, “The Low-Energy Frontier of Particle Physics,” *Ann. Rev. Nucl. Part. Sci.* **60** (2010) 405 [arXiv:1002.0329 [hep-ph]].
- [12] C. Csaki et al., “Super GZK photons from photon axion mixing,” *JCAP* **0305** (2003) 005 [hep-ph/0302030].
- [13] A. De Angelis, M. Roncadelli and O. Mansutti, “Evidence for a new light spin-zero boson from cosmological gamma-ray propagation?,” *Phys. Rev. D* **76** (2007) 121301 [arXiv:0707.4312 [astro-ph]].
- [14] A. De Angelis, G. Galanti and M. Roncadelli, “Relevance of axion-like particles for very-high-energy astrophysics,” *Phys. Rev. D* **84** (2011) 105030 [Erratum: *Phys. Rev. D* **87** (2013) 10, 109903] [arXiv:1106.1132 [astro-ph.HE]].
- [15] M. Simet, D. Hooper and P. D. Serpico, “The Milky Way as a Kiloparsec-Scale Axionscope,” *Phys. Rev. D* **77** (2008) 063001 [arXiv:0712.2825 [astro-ph]].
- [16] M. Fairbairn, T. Rashba and S. V. Troitsky, “Photon-axion mixing and ultra-high-energy cosmic rays from BL Lac type objects - Shining light through the Universe,” *Phys. Rev. D* **84** (2011) 125019 [arXiv:0901.4085 [astro-ph.HE]].
- [17] A. Payez et al., “Revisiting the SN1987A gamma-ray limit on ultralight axion-like particles,” *JCAP* **1502** (2015) 02, 006 [arXiv:1410.3747 [astro-ph.HE]].
- [18] M. S. Pshirkov, P. G. Tinyakov and F. R. Urban, “New limits on extragalactic magnetic fields from rotation measures,” arXiv:1504.06546 [astro-ph.CO].
- [19] M. Meyer, D. Horns and M. Raue, “First lower limits on the photon-axion-like particle coupling from very high energy gamma-ray observations,” *Phys. Rev. D* **87** (2013) 3, 035027 [arXiv:1302.1208 [astro-ph.HE]].
- [20] A. Abramowski et al. [HESS Collaboration], “Constraints on axionlike particles with H.E.S.S. from the irregularity of the PKS 2155–304 energy spectrum,” *Phys. Rev. D* **88** (2013) 10, 102003 [arXiv:1311.3148 [astro-ph.HE]].
- [21] J. Biteau and D. A. Williams, “The extragalactic background light, the Hubble constant, and anomalies: conclusions from 20 years of TeV gamma-ray observations,” arXiv:1502.04166 [astro-ph.CO].
- [22] W. Essey and A. Kusenko, “A new interpretation of the gamma-ray observations of active galactic nuclei,” *Astropart. Phys.* **33** (2010) 81 [arXiv:0905.1162].
- [23] J. Aleksic et al. [MAGIC Collaboration], “MAGIC discovery of VHE Emission from the FSRQ PKS 1222+21,” *Astrophys. J.* **730** (2011) L8 [arXiv:1101.4645 [astro-ph.HE]].
- [24] G. Raffelt and L. Stodolsky, “Mixing of the Photon with Low Mass Particles,” *Phys. Rev. D* **37** (1988) 1237.
- [25] D. Horns et al., “Hardening of TeV gamma spectrum of AGNs in galaxy clusters by conversions of photons into axion-like particles,” *Phys. Rev. D* **86** (2012) 075024 [arXiv:1207.0776 [astro-ph.HE]].
- [26] S. Andriamonje et al. [CAST Collaboration], “An Improved limit on the axion-photon coupling from the CAST experiment,” *JCAP* **0704** (2007) 010 [hep-ex/0702006].
- [27] A. Ayala et al., “Revisiting the bound on axion-photon coupling from Globular Clusters,” *Phys. Rev. Lett.* **113** (2014) 19, 191302 [arXiv:1406.6053 [astro-ph.SR]].
- [28] F. Tavecchio, M. Roncadelli and G. Galanti, “Photons to axion-like particles conversion in Active Galactic Nuclei,” *Phys. Lett. B* **744** (2015) 375 [arXiv:1406.2303 [astro-ph.HE]].
- [29] A. Dobrynina, A. Kartavtsev and G. Raffelt, “Photon-photon dispersion of TeV gamma rays and its role for photon-ALP conversion,” *Phys. Rev. D* **91** (2015) 8, 083003 [arXiv:1412.4777 [astro-ph.HE]].
- [30] R. Beck and R. Wielebinski, *Magnetic fields in galaxies, Planets, Stars and Stellar Systems*, Vol. 5: Galactic Structure and Stellar Populations, ed. G. Gilmore, Springer, Berlin 2013 [arXiv:1302.5663 [astro-ph.GA]].
- [31] D. Moss and A. Shukurov, “Turbulence and magnetic fields in elliptical galaxies,” *Mon. Not. Roy. Astron. Soc.* **279** (1996) 229.
- [32] F. Tavecchio et al., “Evidence for an axion-like particle from PKS 1222+216?,” *Phys. Rev. D* **86** (2012) 085036 [arXiv:1202.6529 [astro-ph.HE]].
- [33] D. Wouters and P. Brun, “Anisotropy test of the axion-like particle Universe opacity effect: a case for the Cherenkov Telescope Array,” *JCAP* **1401** (2014) 016 [arXiv:1309.6752 [astro-ph.HE]].
- [34] D. Harari, S. Mollerach and E. Roulet, “The Toes of the ultrahigh-energy cosmic ray spectrum,” *JHEP* **9908** (1999) 022 [astro-ph/9906309].
- [35] M. Pshirkov, G. Rubtsov and S. Troitsky, work in progress.
- [36] M. S. Pshirkov, P. G. Tinyakov, P. P. Kronberg and K. J. Newton-McGee, “Deriving global structure of the Galactic Magnetic Field from Faraday Rotation Measures of extragalactic sources,” *Astrophys. J.* **738** (2011) 192 [arXiv:1103.0814 [astro-ph.GA]].
- [37] R. Jansson and G. R. Farrar, “A New Model of the Galactic Magnetic Field,” *Astrophys. J.* **757** (2012) 14 [arXiv:1204.3662 [astro-ph.GA]].
- [38] M. Meyer and J. Conrad, “Sensitivity of the Cherenkov Telescope Array to the detection of axion-like particles at high gamma-ray opacities,” *JCAP* **1412** (2014) 12, 016 [arXiv:1410.1556 [astro-ph.HE]].
- [39] R. Durrer and A. Neronov, “Cosmological Magnetic Fields: Their Generation, Evolution and Observation,” *Astron. Astrophys. Rev.* **21** (2013) 62 [arXiv:1303.7121 [astro-ph.CO]].
- [40] K. Dolag, D. Grasso, V. Springel and I. Tkachev, “Constrained simulations of the magnetic field in the local Universe and the propagation of UHECRs,” *JCAP* **0501** (2005) 009 [astro-ph/0410419].



- [41] S. Furlanetto and A. Loeb, “Intergalactic magnetic fields from quasar outflows,” *Astrophys. J.* **556** (2001) 619 [astro-ph/0102076].
- [42] G. Sigl, F. Miniati and T. A. Ensslin, “Ultrahigh-energy cosmic rays in a structured and magnetized universe,” *Phys. Rev. D* **68** (2003) 043002 [astro-ph/0302388].
- [43] S. Bertone, C. Vogt and T. Ensslin, “Magnetic Field Seeding by Galactic Winds,” *Mon. Not. Roy. Astron. Soc.* **370** (2006) 319 [astro-ph/0604462].
- [44] H. Tashiro, W. Chen, F. Ferrer and T. Vachaspati, “Search for CP Violating Signature of Intergalactic Magnetic Helicity in the Gamma Ray Sky,” *Mon. Not. Roy. Astron. Soc. Lett.* **445** (2014) L41 [arXiv:1310.4826 [astro-ph.CO]].
- [45] W. Chen, J. H. Buckley and F. Ferrer, “Evidence for GeV Pair Halos around Low Redshift Blazars,” arXiv:1410.7717 [astro-ph.HE].
- [46] M. Actis *et al.* [CTA Consortium Collaboration], “Design concepts for the Cherenkov Telescope Array CTA: An advanced facility for ground-based high-energy gamma-ray astronomy,” *Exper. Astron.* **32** (2011) 193 [arXiv:1008.3703 [astro-ph.IM]].
- [47] J. Albert i Fort *et al.*, “Physics and astrophysics with a ground-based gamma-ray telescope of low energy threshold,” *Astropart. Phys.* **23** (2005) 493.
- [48] N. M. Budnev *et al.* [TAIGA Collaboration], “TAIGA the Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy - present status and perspectives,” *JINST* **9** (2014) 09, C09021.
- [49] D. D. Dzhappuev *et al.*, “Search for cosmic gamma rays with the Carpet-2 extensive air shower array,” arXiv:1511.09397 [astro-ph.HE].
- [50] S. Cui *et al.* [LHAASO Collaboration], “Simulation on gamma ray astronomy research with LHAASO-KM2A,” *Astropart. Phys.* **54** (2014) 86.
- [51] M. Tluczykont *et al.*, “The ground-based large-area wide-angle gamma-ray and cosmic-ray experiment HiSCORE,” *Adv. Space Res.* **48** (2011) 1935 [arXiv:1108.5880 [astro-ph.IM]].
- [52] R. Beck and B. M. Gaensler, *New Astron. Rev.* **48** (2004) 1289 doi:10.1016/j.newar.2004.09.013 [astro-ph/0409368].
- [53] R. Beck, *Rev. Mex. Astron. Astrof. Ser. Conf.* **36** (2009) 1 [arXiv:0804.4594 [astro-ph]].
- [54] I. G. Irastorza *et al.*, “Towards a new generation axion helioscope,” *JCAP* **1106** (2011) 013 [arXiv:1103.5334 [hep-ex]].
- [55] R. Bahre *et al.*, “Any light particle search II - Technical Design Report,” *JINST* **8** (2013) T09001 [arXiv:1302.5647 [physics.ins-det]].